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Comparative evaluation of changes in soil bio-chemical properties after application of traditional and enriched vermicompost

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ABSTRACT

For nutrient-deficient soils, vermicompost is an excellent soil additive. We find biochemical fluctuations in soil by comparing enriched vermicomposts to regular vermicomposts in a carefully controlled pot experiment. Various rock minerals, including mica, dolomite, and rock phosphate (RP), were used to create the enriched vermicompost before it was applied to acid lateritic soil, and so we investigated how vermicompost's biochemical impact on the soil evolves (15-day intervals). Our results suggested that traditional vermicompost (VC) prepared from water hyacinth effectively improves nutrient content, enzymatic activities, and soil microbial properties. However, enriched VC application significantly ($p<0.05$) augments the concentration of available P (60% higher than conventional VC) and exchangeable K (increased by 10% from conventional VC) in soil. Furthermore, we observed that enrichment of VC using a combination of rock minerals showed significantly higher urease (around 35%), acid phosphatase activity (by 93%), and enhanced microbial biomass carbon (about 25%) and nutrient content of soil compared to only rock mineral additions. Nevertheless, our study revealed that conventional VC shows better soil organic carbon build-up than rock-based enriched VC. Although, enrichment conferred differential benefits to the soil in terms of increased P in RP-based and raised K in MC-based VC.

1. Introduction

We need to conserve non-renewable natural resource bases like soil and maximize the use of renewable resources like organic wastes; therefore, agriculture must rely on sustainable recycling practices. The amount of biodegradable organic waste produced yearly is rising in India and is expected to be on the scale of billion tonnes (Alok, 2014). One of the most dependable and economical methods of supplying nutrients to soils assented by field crops is recycling agricultural waste back into the soil. For instance, onion waste residues, pineapple waste, ageratum weed, sugarcane bagasse, soybean meal waste, essential oil industrial wastes, sago waste, potato waste, and vegetable trash have been tried in the past and

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reported as suitable recycling intrants to agricultural land (Ahmed and Deka, 2022; Boruah et al., 2019; Cai et al., 2022; Das and Deka, 2021; Ganguly and Chakraborty, 2019; Karmegam et al., 2021).

However, the enormous prospect of such recycling lies in exploring more convenient ways to recycle these biggest underused resources in our country in the form of animal and plant wastes (Das et al., 2021). Researchers have underlined that one of the major reasons behind this is the lack of a viable method for their recycling. Recycling waste materials requires the controlled biological oxidative degradation of organic matter like composting (Said-Pullicino et al., 2007). However, composting has certain drawbacks, such as nutrient leaching throughout the process, high land costs, manpower and equipment requirements, and unpleasant stench. However, providing modified or alternate methods to obtain affordable, high-quality organic manures is essential for sustainable agriculture. From this standpoint, vermicomposting has been acknowledged as an environmentally beneficial method for turning organic wastes into highly-valuable organic manure. In terms of lowering greenhouse gas emissions and improving the finished product's nutrient content, vermicomposting is superior to composting. Earthworms and microorganisms may thrive and function better in aerobic and mesophilic environments. Therefore, vermicomposting could speed up the breakdown of materials rich in lignocellulose. The earthworm produces mucus and enzymes that may help the vermicomposting process break down cellulose more quickly (Cai et al., 2022). For that reason, Vermicompost (VC) can be used to improve soil fertility and health beyond time by ensuring biochemical restitution (Raja et al., 2022).

Acid lateritic soils are generally impoverished in organic matter content owing to high temperature, rainfall, and intense microbial activity (Biswas and Mukherjee, 2000). Additionally, this soil requires constant fertilization to maintain the optimum crop yield potential. The conventional methods to supply nutrients to such soils reduce the soil's organic matter content and fertility (Abbhishek et al., 2021). Therefore, to maintain soil fertility and crop productivity, in the long run, organic fertilizers like enriched VC are added to replenish the organic carbon. It increases soil organic carbon content (Abbhishek et al., 2021, 2022) and improves the lateritic soil's health and fertility (Kumar and Swain, 2021).

The soil organic carbon content is the backbone of soil organic matter, a reservoir of nutrients and positively influences soil microbial activities that indicate the soil quality for sustainable crop production. Organic fertilizers are vital as a source of soil humus and plant macro and micronutrients. However, conventional VC is not efficient enough to provide plants with the necessary quantity of macro and micronutrients precisely as per the crop's need. As a result, there is an opportunity to improve the nutrient contents of VC to ensure that they are delivered to crops quickly and effectively.

According to the UNFC (2013), India has access to about 296 million tonnes of rock phosphate (RP), the majority of which is unsuitable for the industrial production of P-fertilizers due to its low accessible P content and low reactivity Narayanasamy and Biswas (1998). In addition, Muriate of potash or sulphate of potash is imported, which costs much foreign currency because India lacks K-rich minerals. Nevertheless, India is lucky to possess the greatest resource of mica, a mineral containing K, found in the Jharkhand districts of Koderma, Giridih, and Hazaribagh (Nishanth and Biswas, 2008). We can use such low-grade ores to transform them using chemical and biological processes as a useable product and an important source of nutrients for plants. For instance, solubilizing the otherwise insoluble K in mica ores through bio-intervention with *Bacillus mucilaginous* may be a practical alternative technique (Basak and Biswas, 2009). Similarly, India has access to roughly 738 million tonnes of dolomite, with high Ca (18 to 22 percent) and Mg content (UNFC, 2014). Adding such natural minerals may ensue enriched VC containing a higher concentration of nutrients through alteration of pH during the vermicomposting process. However, we have a dearth of experimental evidence originating from such enriched manure preparations using low-grade rock phosphate, dolomite, and mica and its effects on changes in soil fertility after an intensive application in acid-lateritic soils.

The above opinions unequivocally show that using traditional VC to maintain and enhance soil fertility is insufficient. To add value and improve quality, VC must be supplemented with additional macro and micronutrients using new technologies. Supplementing vermicomposting technology with current agricultural practices while maintaining the nutrient management package will be a better option for reconciling sustainability and agricultural soil productivity. Using rock minerals, microbial inoculum and animal wastes to enrich traditional VC to impart impetus to lateritic soil fertility requires more attention.

This is the first time we have tried adding rock minerals (DM and MC, except RP) to the vermicomposting process to increase the solubility of nutrients apart from enriching the source strength as such. Furthermore, the comparative results for incorporating rock minerals during the vermicomposting process are scarce. We also have a little information on the optimized amounts of rock minerals required during vermicomposting (i.e., based on earthworm tolerance capability) to produce a higher-quality organic fertilizer. However, technological advancements sought to improve the vermicompost by adding various rock minerals. Considering the research gap in upgradation and technological advancement in preparation of vermicompost, we evaluated the impacts of enriched VC compared to traditional VC for soil nutrient dynamics and enzyme activity. Our objective is to prepare and evaluate the potential of enriched VC vis-à-vis conventional VC through the ultimate analysis of nutrient properties.

2. Material and methods

2.1. Rock minerals

The VC was enriched with phosphorus (P), calcium–magnesium (Ca–Mg), and potassium (K) using the rock minerals rock phosphate (RP), dolomite (DM), and mica (MC), respectively. The West Bengal Mineral Development and Trading

Corporation Limited in Purulia, West Bengal provided the RP and DM, and Prakash Pvt. Ltd. in Jharkhand provided the mica waste. The material was ground to pass through a 2 mm sieve. RP contains 85.2 mg g^{-1} total P, 0.04 mg g^{-1} olsen P, 3 mg g^{-1} total K, 81.20 mg g^{-1} total Ca, and 48.20 mg g^{-1} of total Mg. DM contains 192.5 mg g^{-1} total Ca and 128.4 mg g^{-1} total Mg. Mica waste contains 101.2 mg g^{-1} total K and a small amount of ammonium acetate K (available K). It contains 0.8 mg g^{-1} total Ca and 45.2 mg g^{-1} total Mg.

2.2. Organic wastes and earthworm species used for vermiconversion

Three plant-based organic wastes, such as water hyacinth/WH (aquatic weeds), paddy straw/PS (a byproduct of rice), and animal waste/cow dung, were used in this study. The quality of these organic wastes differed concerning the C/N ratio, i.e., 48:1 for water hyacinth, 67:1 for paddy straw, and 32:1 for cow dung. The waste materials like paddy straw and water hyacinth were collected from the research farm of the Institute, sawdust was collected from the nearest sawmill at Kharagpur, and fresh cow dung was procured from adjacent cattle dairy farm. In addition, the exotic epigeic earthworm '*Eisenia foetida*' was used in the vermicomposting process. Each of the earthworm stocks cultures containing 500–2000 earthworms was maintained in the laboratory with cow dung as culturing material.

2.3. Microbial source

Pure cultures of microbial inoculants used in the composting process were *Trichoderma viride, TV* (cellulolytic and lignolytic fungi), *Azotobacter chroococcum, AZC* (free-living nitrogen-fixing bacteria, for enriching nitrogen), *Bacillus polymixa, PSB* (phosphorus-solubilizing bacteria, for improving phosphorus), and *Bacillus firmus, KSB* (potassium-releasing bacteria for enhancing potassium). The microbial inoculants, *TV, AZC,* and *KSB* were procured from the Institute of Microbial Technology, Chandigarh, India. Other bacteria *KSB* was collected from the Department of Agricultural Microbiology, Indian Agricultural Research Institute, New Delhi, India. The fungal cultures were maintained by Potato Dextrose Agar Media, while bacterial inoculations were sub-cultured on Jensen's Agar Media.

2.4. Preparation of rock mineral-enriched vermicompost

In separate earthen pots, one kilogramme (dry weight basis) of the organic wastes (WH and PS) and fresh cow dung were combined in a 1:1 ratio (each pot diameter: 15 cm and depth: 15 cm). The calculated amounts of rock minerals (RP, DM, and MC) were then added to the two organic wastes in the prescribed doses. The combinations of microbes such as TV, AZC, PSB, and KSB were inoculated with the rock minerals in both the organic wastes. The microbial inoculation was done as 50 mL of seven-day-old broth culture per kg (10^6 cells per mL) of these organic wastes. Regular turning of the material and sprinkling of water was done manually to eliminate volatile toxic gases and maintain the temperature in the range of 30–35 °C for mesophilic aerobic digestion. The moisture was kept in the range of 60%–70%. The VC was continued up to 105 days till the C/N ratio became constant.

2.5. Characterization of rock mineral enriched vermicompost

At maturity (after 105 days), the VCs were drawn from each pot. A representative sample was drawn from each product and divided into two portions. One portion was kept in a refrigerator at four degree-Celcius and used subsequently for analysis of total N, mineralizable N (NH_4^+-N and NO_3^--N) content, urease assay, and acid phosphatase assay. The other portion was first air dried (25–30 °C) for 24 h, crushed, passed through a 2-mm sieve, and used to analyse organic C, total P, and K, and available P and K. The representative samples drawn from each pot were analysed for the fresh samples' moisture content to express the data on a dry-weight basis.

The pH was determined using a double distilled water suspension of VC in the ratio of 1:10 (W/V) that was agitated mechanically for 30 min and filtered through the Whatman no. 1 filter paper (Page et al., 1982). Organic C content in samples was determined by the dichromate oxidation method in the acid mediums (Nelson and Sommers, 1982). One gram of VC was first digested in 25 mL of concentrated HNO_3 followed by 20 mL of 60% $HClO_4$, and total P content was determined by spectrophotometer after developing the vanado-molybdo-phosphoric yellow colour complex in the nitric acid mediums (Jackson, 1973).

$$Organic\ Carbon\ (\%) = \frac{10}{Blank} \times (Blank - Reading\ for\ sample) \times \frac{0.003 \times 100}{Weight\ of\ soil}$$

For the estimation of olsen P (available P), 2.5 g of sample was extracted with 50 mL of 0.5 M $NaHCO_3$ (pH 8.5) for 30 min (Olsen et al., 1954), and phosphate content was determined spectrophotometrically using ascorbic acid as the reductants following the procedure given by (Watanabe and Olsen, 1965).

$$\text{Phosphorus (ppm)} = \frac{Q \times V}{A \times S}$$

where, Q = quantity of Phosphorus (P) in ppm reading on X axis against a sample, V = volume of extracting reagent used (mL), A = volume of aliquot used for colour development (mL), and S = weight of soil sample taken (g).

Table 1
Estimation of chemical parameter of enriched vermicomposts used in the experiment by following method and references.

Chemical properties	Method	References
Organic C	Dichromate oxidation	Nelson and Sommers (1982)
Total N	Kjeldahl digestion	
Total P	Vanadomolybdo complex followed by spectrophotometric	Jackson (1973)
Total K	Di-acid digestion	
Olsen P	Spectrophotometric	Watanabe and Olsen (1965)
Inorganic N (NH_4^+-N and NO_3^--N)	Extraction cum distillation	Keeney and Nelson (1982)
Available K	Flame photometric method	Hanway and Heidel (1952)

Ammonium acetate K (available K) was determined by extracting a 5 g sample by 25 mL 1N NH_4OAc (pH 7.0), as outlined by Hanway and Heidel (1952). A flame photometer then estimated the potassium concentration in the extract. Inorganic N ($NH_4{}^+$-N and $NO_3{}^-$-N) was determined by first extracting the samples with 2M KCl (sample solution ratio of 1:10), followed by the determination of $NH_4{}^+$-N by steam distillation with MgO in a micro-Kjeldahl distillation unit (Keeney and Nelson, 1982). The same procedure was used for $NO_3{}^-$-N after the reduction of Devarda's alloy

$$\text{Nitrogen (\%)} = \frac{(Titre\ reading - Blank\ reading)\ mL \times Normality\ of\ Acid \times 14 \times 100}{Weight\ of\ soil\ (g) \times 1000}$$

$$\text{Potassium (ppm)} = \text{C} \times \frac{25\ \text{mL}\ 1\ (N)\ Ammonium\ acetate\ solution}{Weight\ of\ soil\ (g)}$$

where, C = The concentration of potassium in the sample obtained on X axis, against the reading (ppm)

Enzymes such as urease and phosphatase activities of soils were estimated following the methods suggested by Tabatabai (1994). These enzyme activity estimations were done for the moist field condition. However, the measured activities were expressed on the basis. Microbial plate counts were made following the method of Travors and Cook (1992).

2.6. Experimental soil

The soil used in the experiment was acid laterite (type-Haplupt) and sandy loam in texture. It is low in organic C and available N content, medium in available P, and low in available K content as explained in Jackson (1973). The detailed physical and chemical characteristics of the soil used in the experiments are presented in Table 1.

2.7. Experimental design to study nutrient dynamics

We examined the nutrient release pattern in acid lateritic soil through a pot experiment. The experiment utilized enriched VC made from rock minerals (RP, DM, and MC) and microbial inoculums. In this experiment, we mixed 4.5 g of enriched VC with 500 g of air-dried soil in earthen pots (diameter: 15 cm and depth: 15 cm) at a 20 t ha^{-1} basis. This incubation used the enriched VC made from organic wastes (WH and PS) with the addition of rock minerals at a 15% dose and microbial inoculum. We evaluated the enriched VC vis-a-vis standard VC through a control treatment maintained without foreign material (other than soil). Conventional VC was also mixed with the soil at a 20 t ha^{-1} basis. The moisture was maintained at field capacity by sprinkling water as and when required. Therefore, we had a total of 26 treatments [{3 (wastes) × 4 (rock mineral enriched VC) × 2 (microbes)} + 1 (conventional VC) + 1 (control, only soil)]. The incubation experiment was carried out in a completely randomized design with three replications. The treatment details are as follows.

Treatment details:

Factor 1: Organic wastes (Three)

a. No organic waste (NW.)
b. Water hyacinth (WH.)
c. Paddy straw (PS.)

Factor 2: Rock minerals (Four)

a. Rock phosphate (RP.)
b. Dolomite (DM.)
c. Mica waste (MW.)
d. RP+DM+MW

Table 2
Selected chemical properties of the acid lateritic soil used to evaluate the effects of vermicomposting with rock mineral enriched vermicompost.

pH (1:2.5)	Organic C (mg g^{-1})	Mineralizable N (mg g^{-1})	Total N (mg g^{-1})	Available P (mg g^{-1})	Total P (mg g^{-1})	Available K (mg g^{-1})	Total K (mg g^{-1})
5.5	3.0	0.07	0.40	0.01	0.20	0.05	0.20

Factor 3: Microbial inoculum (Two)

a. No microbes (M0)
b. Microbes (TV+AZC+PSB+KSB) (M1)

Moist soil samples were drawn from each pot after incubating for 15, 30, 45, 60, 75, and 90 days. Then organic carbon, available nitrogen (mineralizable nitrogen), available phosphorus, and available potassium were estimated at 15 days intervals up to 90 days, and microbial biomass carbon, urease activity, and acid phosphatase activity was estimated at 30 days intervals to 90 days period of study. Available micronutrients (Fe, Mn, and Zn) and available Ca and Mg were assessed after 90 days.

2.8. Statistical analysis

As mentioned above, the data from the trials were examined using a three-way ANOVA following Gomez and Gomez (1984), post-hoc and t-test was carried out for paired comparisons using SPSS statistical software. The ANOVA is helpful to gauge complex interactions like in the enrichment of VC and whether they are due to chance or factors in the analysis. We identified the significant differences between the treatment means, and all treatment results were compared using the least significant difference (LSD) values at P = 0.05.

3. Results

3.1. Composition of enriched rock mineral enriched vermicompost

In contrast to traditional VC, we observed that the OC content in the matured VC significantly decreased with RP, DM, and MC enrichment. The mean OC level of conventional VC was 243.3 mg g^{-1}, but it considerably reduced in the enrichment process of VC, specifically with DM, MC, and RP, to 197.7, 176.9, and 165.6 mg g^{-1}, respectively. The RP-enriched VC had a substantially higher content of total P (23.0 mg g^{-1}) compared to conventional VC (9.3 mg g^{-1}), where no mineral was added. Furthermore, we observed that DM-based VC had 16.4 mg g^{-1} total N, traditional VC had 14.0 mg g^{-1}, MC-based VC had 12.1 mg g^{-1}, and RP-based VC had 12.0 mg g^{-1}. As a result, all-enriched VCs had lower C/N ratios than regular VCs, regardless of treatment, compared to conventional VC. Nevertheless, we observed the concentration of nutrients as the total N content of waste materials, i.e., WH and PS increased significantly in all matured VC. Among the VCs, the highest total P content (23 mg g^{-1}) was observed in RP-enriched VC, followed by conventional VC (9.3 mg g^{-1}), DM-based VC (8.1 mg g^{-1}) and MC-based VC (7.6 mg g^{-1}). On the other hand, total K content also increased substantially in MC-enriched VC (24.9 mg g^{-1}) and RP-enriched VC (15.5 mg g^{-1}) as compared to DM and conventional VC (11.2 mg g^{-1}).

However, as far as available N is concerned, DM-enriched VC had higher available N content (3.8 mg g^{-1}), followed by conventional VC (2.9 mg g^{-1}), RP-based VC (2.3 mg g^{-1}) and MC-based VC (1.5 mg g^{-1}). Available P (Olsen P) content (2.4 mg g^{-1}) was significantly increased when the VC was prepared with RP compared to other adjuvants. Similarly, available K (ammonium acetate K) content (9.3 mg g^{-1}) showed a maximum in MC-enriched VC among all preparations (Table 2). Alternatively, DM-based VC showed significantly higher UA content, followed by RP and MC-based VC. An upsurge in UA content (137 μg NH_4 g^{-1} h^{-1}) was observed in enriched VC compared to conventional VC. Similarly, RP-based VC had higher APA content (222 μg pnp g^{-1} h^{-1}) than traditional VC (142 μg pnp g^{-1} h^{-1}).

3.2. Incubation experiment

3.2.1. Changes in chemical properties of acid lateritic soil

The OC content of VC amended soil decreased slowly from 0 days of incubation (DOI) towards the end of the experiment (90 DOI) (Fig. 1). The variation in OC content of control soil was marginal during the incubation period. Our results show that the OC content of soil treated with only rock minerals was significantly lower than the rest of treatments. Among the rock mineral enriched VC applications, RP and DM were comparable (5 mg g^{-1} and 4.9 mg g^{-1}), and both were significantly superior to MC (4.4 mg g^{-1}) and combined rock minerals-based VC (3.7 mg g^{-1}) in building SOC. Furthermore, with the application of VC, a gradual increase in the soil's available N content was noted from 0 DOI to 60 DOI, and after that, it

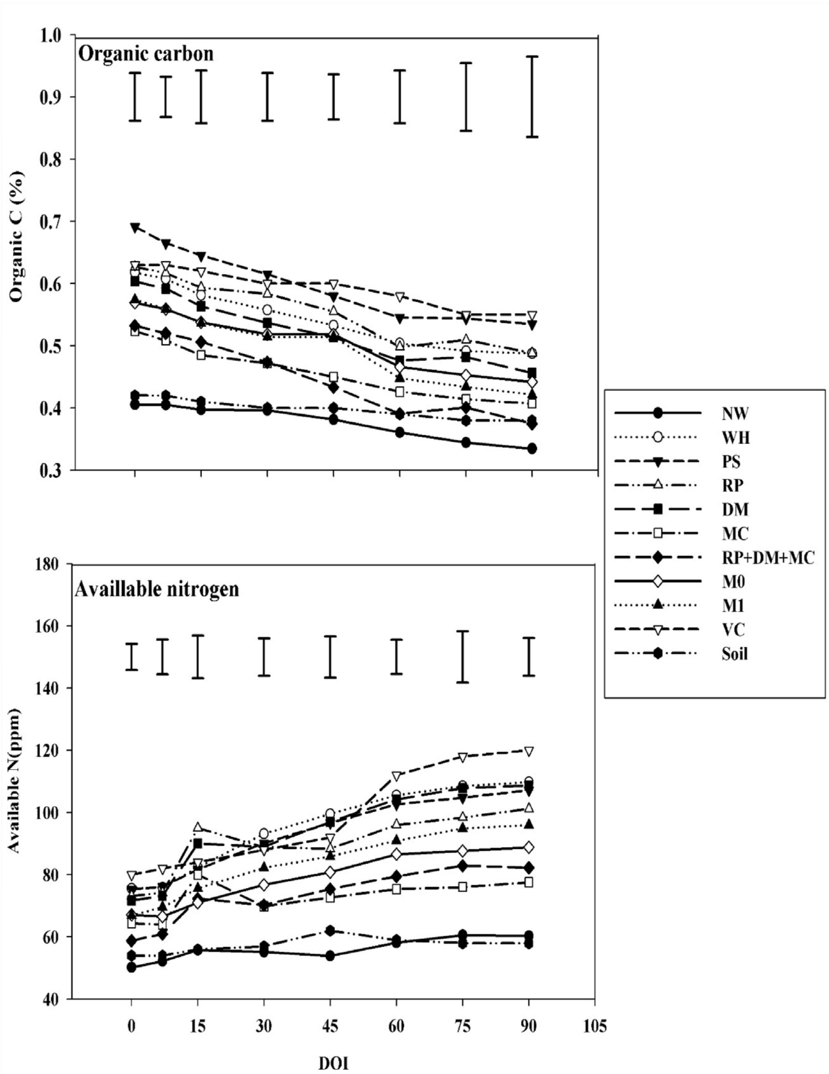

Fig. 1. Time series of organic carbon and available nitrogen content in days of incubation (DOI) of enriched vermicompost. The vertical lines indicate standard error; NW: no waste (only rock minerals); RP: rock phosphate; DM: dolomite; MC: mica; RP+DM+MC: mixed mineral; M0: without microbial inoculants; M1: with microbial inoculants; VC: conventional vermicompost.

remained almost constant (90DOI) (Fig. 1). Conventional VC resulted in higher available N content of the soil as compared to rest treatments throughout the incubation period. The available N content of soil added with different rock minerals-based VC followed an order of significance as DM (109 ppm) > RP (101 ppm) > Integration of rock minerals (RP + DM + MC) (82 ppm) > MC VC (77 ppm).

After adding enriched VC, the available soil P content sharply increased up to 45 DOI; after that, the increase was marginal in most treatments (Fig. 2). The available soil P content with enriched VC was significantly higher than conventional VC and control throughout the incubation period. RP-based VC registered the maximum available P content of soil (40 ppm), which was followed by mixed rock minerals VC (RP+DM+MC) (25 ppm), DM (21 ppm) and MC (9 ppm). The application of enriched VC resulted in a gradual increase in the available K content up to 75 DOI. For the treatment control and NW application, the soil available K content remained almost similar throughout the incubation period, the lowest being in NW treatment. Among the rock minerals enriched VC, MC-based VC registered the highest available K content of soil (131 ppm), which was significantly followed by the integration of rock minerals (127 ppm), RP (81 ppm) and DM (74 ppm).

Rock minerals enriched VC upstretched the pH of lateritic soils towards a neutral range, as shown in Fig. 3. However, the efficiency of the various VCs varied. We detected a considerably higher soil pH in DM-based VC (6.77) than in RP (6.13) and MC-based VC (5.51). (5.91). Still, the enriched VC using RP, DM, and MC reflected lower pH than conventional VC (7.8).

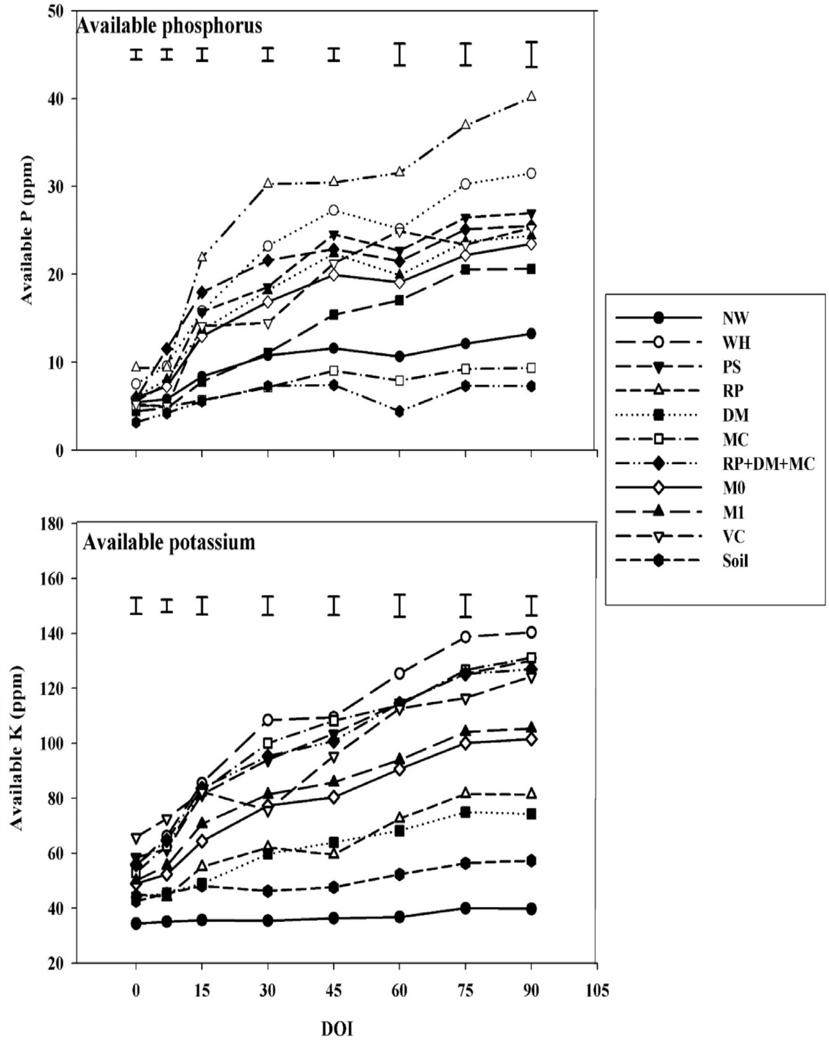

Fig. 2. Time series of available phosphorus and available potassium content in days of incubation (DOI) of enriched vermicompost. The vertical lines indicate standard error; NW: no waste (only rock minerals); RP: rock phosphate; DM: dolomite; MC: mica; RP+DM+MC: mixed mineral; M0: without microbial inoculants; M1: with microbial inoculants; VC: conventional vermicompost.

Among the rock minerals enriched VC, Integration of all rock minerals (RP+DM+MC) increased the soil available Ca content significantly more than other individual rock minerals (Fig. 4). The available Ca content with rock minerals enriched VC followed the order of RP+DM+VC (488 ppm) > DM (470 ppm) > RP (463 ppm) > MC (360 ppm). Nevertheless, among the rock minerals enriched VC, RP+DM+VC and DM were comparable, and they were significantly better than RP and MC in increasing the available Mg content of the soil.

Among the rock minerals enriched VC, MC-based VC registered the maximum available Fe content of soil (∼123 ppm), which was significantly higher than the rest of the treatments (Fig. 5). Treatment involving only rock minerals application was comparable to control for the available Mn content of the soil. Among the rock minerals enriched VC, mixed mineral VC (RP+DM+MC) was significantly superior to rest mineral enriched VC in increasing the available Mn content of soil. Among the rock minerals enriched VC, RP was more effective than the rest formulations in increasing the available Zn content of the soil.

3.2.2. Changes in biochemical properties of acid lateritic soil

Urease assay (UA) of soil was noted with an increase after the addition of enriched VC as compared to conventional VC throughout the incubation period (Fig. 6). The WH, PS, and Integration of rock minerals (RP+DM+VC) based VC gave higher UA results as compared to rest enriched VC throughout the incubation period.

Among the rock mineral enriched VC, RP+DM+VC and RP noted significantly higher UA (60 μg NH_4 g^{-1} h^{-1} and 57 μg NH_4 g^{-1} h^{-1} respectively) than the rest of the rock mineral treatments. Application of enriched VC resulted in a gradual

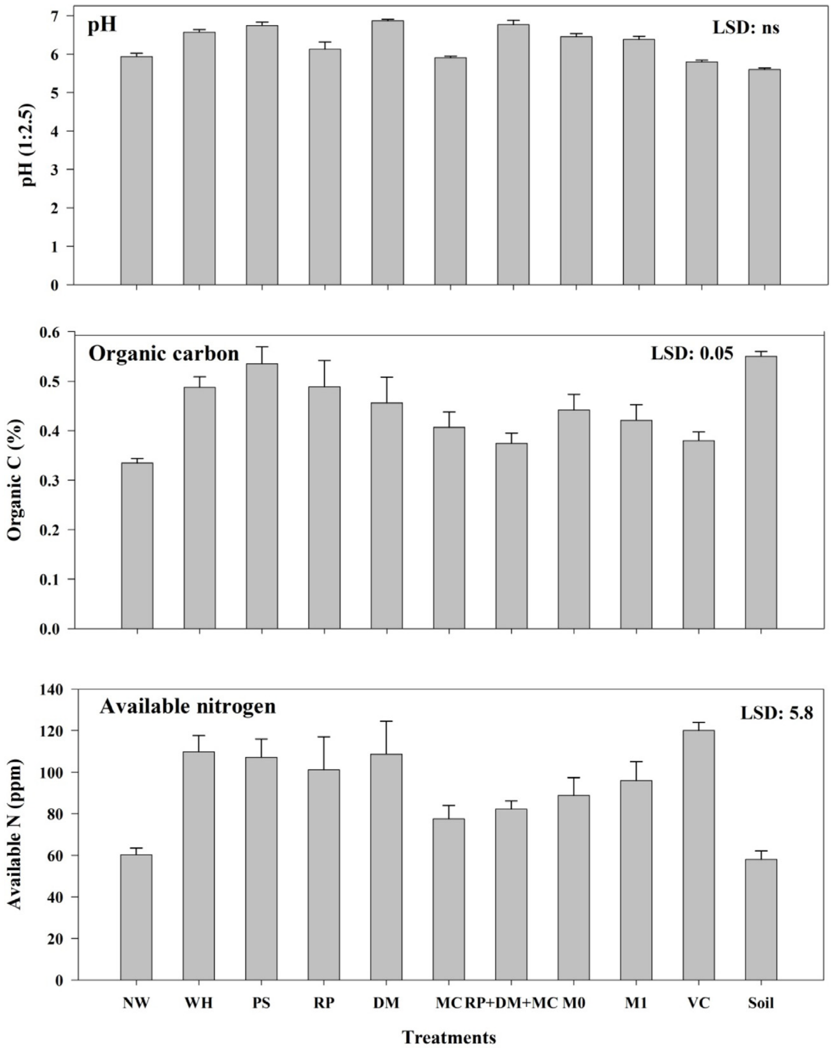

Fig. 3. Chemical properties (pH, organic carbon and available nitrogen) of soil as affected by different enriched vermicomposts; The vertical lines indicate standard error. LSD: least significance difference at P = 0.05; ns: non-significant; NW: no waste (only rock minerals); RP: rock phosphate; DM: dolomite; MC: mica; RP+DM+MC: mixed mineral; M0: without microbial inoculants; M1: with microbial inoculants; VC: conventional vermicompost.

decrease of soil acid phosphatase activity (APA) up to 60 DOI. After that, the increase was marginal in all treatments except PS, RP, and RP+DM+MC enriched VC (Fig. 6). Integration of rock minerals RP+DM+MC and RP-based VC reflected higher APA compared to rest treatments throughout the incubation period.

Among the rock minerals enriched VC, Integration of rock minerals (RP+DM+MC) was most effective in increasing APA of soil (452 μg pnp g^{-1} h^{-1}), which was significantly followed by RP (408 μg pnp g^{-1} h^{-1}), DM (215 μg pnp g^{-1} h^{-1}) and MC based VC (207 μg pnp g^{-1} h^{-1}). The lowest MBC was recorded for only rock mineral-added treatments (NW). Among the rock mineral enriched VC, RP resulted in significantly higher MBC content of soil than other rock minerals. The MBC content of soil added with rock minerals enriched VC followed the order in significant: RP (2007 μg g^{-1}) > RP+DM+VC (2000 μg g^{-1}) > DM (1837 μg g^{-1}) > MC (1605 μg g^{-1}).

3.2.3. Relationship between the soil organic carbon and soil biological properties

Data from the correlation matrix of different soil properties (Table 3) revealed that the OC was significantly and positively correlated with urease ($r = 0.74$, $P < 0.01$), acid phosphatase ($r = 0.61$, $P < 0.01$), BSR ($r = 0.42$, $P < 0.05$), qCO2 ($r = 0.47$, $P < 0.05$). Similarly, a positive and significant correlation between MBC and acid phosphatase ($r = 0.64$, $P < 0.05$), BSR ($r = 0.93$, $P < 0.05$) and qCO2 ($r = 0.57$, $P < 0.05$) and MBC/OC ($r = 0.65$, $P < 0.05$) were also observed.

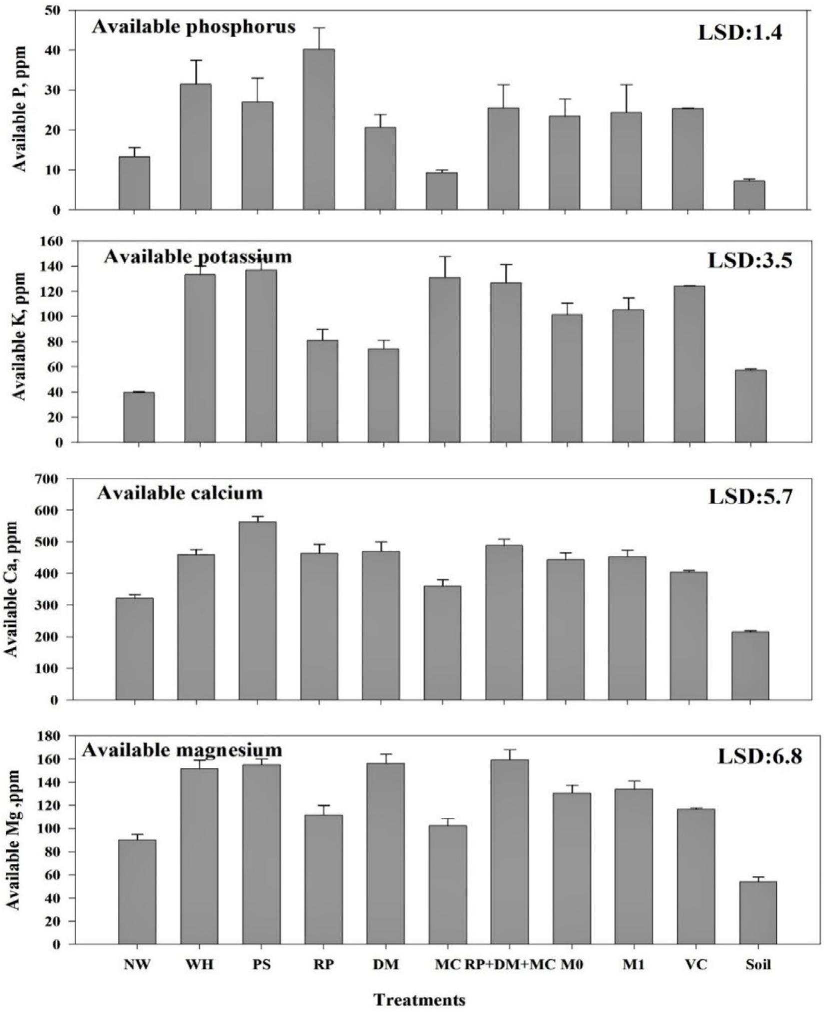

Fig. 4. Chemical properties of macro nutrients (available phosphorus and available potassium) and major nutrients (available calcium and magnesium) of soil as affected by different enriched vermicomposts; The vertical lines indicate standard error. LSD: least significance difference at P = 0.05; NW: no waste (only rock minerals); RP: rock phosphate; DM: dolomite; MC: mica; RP+DM+MC: mixed mineral; M0: without microbial inoculants; M1: with microbial inoculants; VC: conventional vermicompost.

Table 3
Characteristics of various enriched vermicomposts prepared by mixing organic wastes (water hyacinth and paddy straw) with rock minerals (Rock phosphate, dolomite and mica) and microbes.

Enriched vermicomposts (at 15% dose)	Organic carbon (mg g^{-1})	Total nitrogen (mg g^{-1})	C/N ratio	Total phosphorus (mg g^{-1})	Total potassium (mg g^{-1})	Inorganic Nitrogen nitrogen (Ammonium +Nitrate) (mg g^{-1})	Olsen phosphorus (mg g^{-1})	Ammonium acetate potassium (mg g^{-1})
RP-based	165.6^{c}	12.0^{c}	14:1	23.0^{a}	15.2^{b}	2.3^{b}	2.44^{a}	4.84^{b}
DM-based	197.7^{b}	16.4^{a}	12:1	8.1^{c}	15.5^{b}	3.1^{a}	1.75^{b}	2.32^{c}
MC-based	177.0^{c}	12.1^{c}	15:1	7.6^{c}	24.9^{a}	1.5^{c}	1.16^{c}	9.27^{a}
Conventional VC	243.3^{a}	14.1^{b}	17:1	9.3^{b}	11.2^{c}	3.8^{a}	1.29^{c}	4.33^{b}

Different alphabets superscripted of the data suggest that the respective data are statistically significant at 5% level.

4. Discussion

4.1. Characteristics of enriched vermicompost

The decrease in OC content in the enriched VC compared to conventional VC can be traced back to the dilution of C content when RP, DM, and MC were added to the composting mass (Nishanth and Biswas, 2008). Nitrogen content in

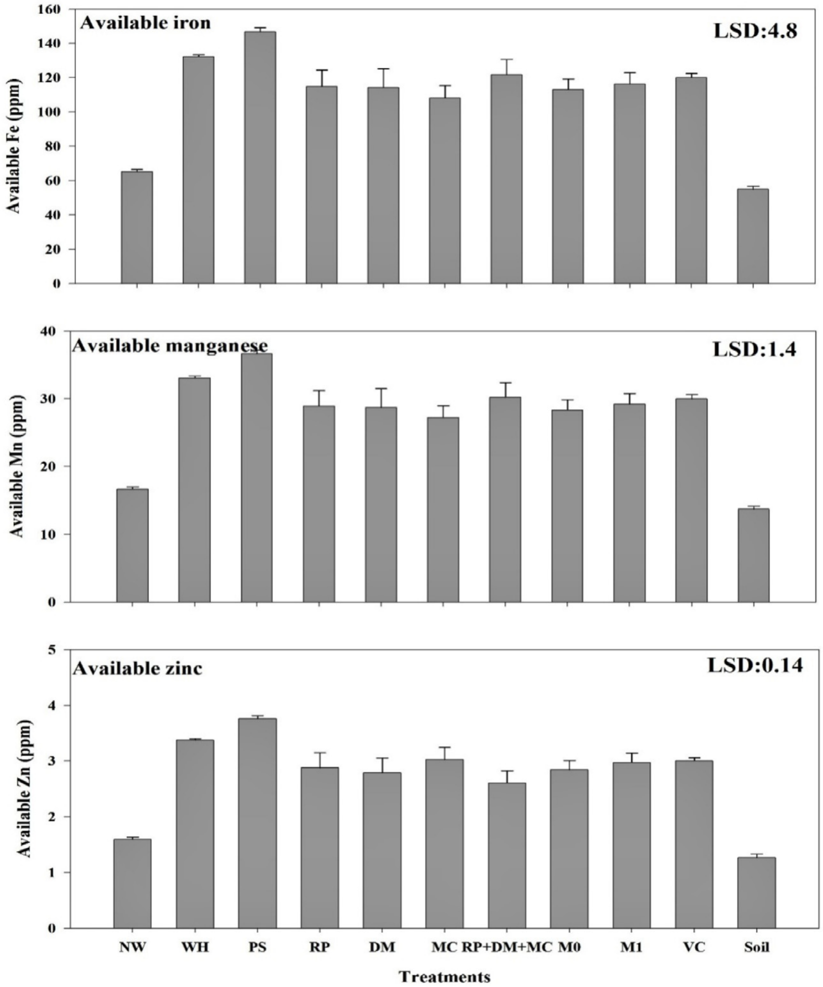

Fig. 5. Chemical properties of micronutrients (available iron, manganese and zinc) of soil as affected by different enriched vermicomposts; The vertical lines indicate standard error. LSD: least significance difference at P = 0.05; NW: no waste (only rock minerals); RP: rock phosphate; DM: dolomite; MC: mica; RP+DM+MC: mixed mineral; M0: without microbial inoculants; M1: with microbial inoculants; VC: conventional vermicompost.

all of the VCs increased significantly during vermicomposting of organic wastes due to loss in their weight accompanied by the evaluation of CO_2 and H_2O during the decomposition of organic matter. Similar results of decreased carbon and increased total N content during the decomposition of organic wastes were also reported by Goyal et al. (2005). The highest N content was observed in conventional VC (14.0 mg g^{-1}), implying that adding minerals (RP, DM, and MC) into the composting mass decreased N content significantly. This might be because RP, DM, and MC contain negligible N and dilute N content per unit mass of the final VC. DM recorded a higher N content among the enriched VCs, which might result from improved nitrogen fixation and an increase in the pH, which several researchers have explained (Coventry and Williams, 1983; Ananthanarayana et al., 1992).

On the other hand, total P content increased significantly in RP-based VC compared to other enriched VCs, which may be attributed to rock phosphate's contribution towards P. The total P and available P content were increased further when inoculated with PSB (*Bacillus polymixa*) in the composting mass. The more P released in the case of RP-based VC, the more organic acids like citric, oxalic, and tartaric acids are produced. Our results show that vermicomposting of organic matter with RP enhanced the dissolution of P.

Furthermore, a lot of CO_2 evolved during the process of decomposition of organic matter, resulting in the formation of weak carbonic acid, which dissolved RP and rendered the enhanced availability of P, thus increasing the efficiency of RP (Chien, 1979; Bangar et al., 1989 and Biswas and Narayanasamy, 2006) . As far as the total K content is concerned, it decreased with RP and DM addition compared to conventional VC; this is obvious because of the dilution effect when RP

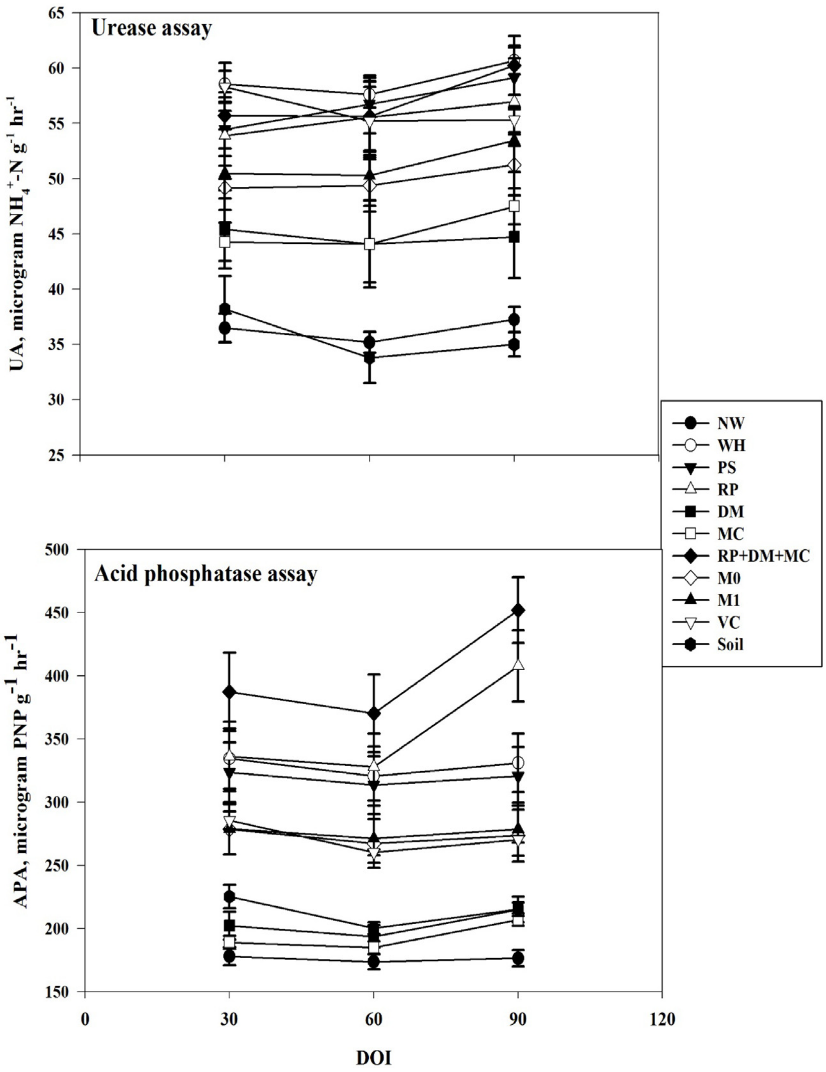

Fig. 6. Time series of biological properties (urease assay and acid phosphatase assay) in DOI of enriched vermicompost. The vertical lines indicate standard error. LSD: least significance difference at P = 0.05; NW: no waste (only rock minerals); RP: rock phosphate; DM: dolomite; MC: mica; RP+DM+MC: mixed mineral; M0: without microbial inoculants; M1: with microbial inoculants; VC: conventional vermicompost.

and DM are incorporated into organic wastes. However, the total K and available K content in the enriched VC increased when waste mica was added to the composting mass. This could be attributed to the contribution of K from MC.

4.2. Incubation experiment

4.2.1. Chemical properties of the soil

It is well established that the application of VC on acid soils can significantly improve the chemical properties if pH is adjusted to near neutral (Padmavathiamma et al., 2008). The relatively higher soil pH noted under enriched VC (pH = 7.3) application compared to conventional VC (pH = 6.8) is attributed to the higher pH value of the former input. An increase in pH in soil amended with organic fertilizer has been reported by Brady and Weil (2002). DM-based enriched VC showed higher soil pH content than the rest of the enriched VCs because of the release of basic cations like Ca^{+2} and Mg^{+2} from DM solubilization. The use of minerals alone showed no variation in pH compared to wastes since they did not have any acid or basic forming ion. Among the wastes, WH-based VC showed lower pH of the acid soil than PS-based VC because WH favoured a higher rate of nitrification that caused the formation of nitric acid, which increased the acidity in the soil (Brallier et al., 1996).

Table 4
Correlation matrix for different soil biological properties after application of different enriched vermicomposts.

Column1	Soil OC	UA	APA	MBC	BSR	MBC/soil OC	qCO2
Soil OC	1	0.75**	0.61**	0.34*	0.42**	0.47**	0.46**
UA		1	0.87**	0.77**	0.77**	0.12	0.60**
APA			1	0.65**	0.69**	0.11	0.59**
MBC				1	0.93**	0.65**	0.57**
BSR					1	0.49**	0.82**
MBC/soil OC						1	0.1
qCO2							1

Soil OC: soil organic carbon, UA: urease activity; APA: acid phosphatase activity; MBC: microbial biomass carbon, BSR: basal soil respiration, qCO_2 : microbial quotient.

The OC content is an indicator of soil fertility, and applications of VC improved the OC content of the lateritic soil indicating the role of organic input in increasing the OC content of lateritic soils, which are generally poor in OC content. However, the decline of the soil OC temporally indicated slow decomposition of organic matter after the application of VC. The application of rock minerals alone did not contribute much to soil OC, which can be attributed to negligible OC content. The DM-based VC application increased soil pH, leading to slow microbial decomposition (Krebs et al., 1998), lowering the mineralization while reflecting the maximum OC content of the soil as compared to other enriched VCs. The higher soil OC content in PS-based and conventional VC treatments was due to higher OC content in these VC compared to WH-based VC (Table 4). The application of microbial-inoculated VC decreased the soil OC content. This was due to the microbes' degradation and consumption of OC and its subsequent release as CO_2 into the atmosphere. Microorganisms like PSB and TV were probably responsible for more significant carbon mineralization and eventually resulted in the lowest OC, hence lowering the C/N ratio of the soil.

An increased available N content in VC-treated soil might be attributed to a higher mineralization rate. Conventional VC resulted in higher N availability in soil due to its higher N content than enriched VC. Among the minerals-enriched VC, DM-based VC resulted in higher N than the rest treatments. The availability of Ca and Mg in DM was responsible for increasing N content by increasing the population of nitrogen-fixing bacteria in soil that mineralized more N (Ananthanarayana et al., 1992), thereby increasing the available N content of the soil. This implies that WH, as a feedstock, increased soil available N content between the wastes more effectively than others due to its lower C/N ratio.

The Higher P content of VC-treated soil might be attributed to the fact that humate and organic anions compete with phosphate ions for the exchange sites of soil colloids (Mengel, 1997; Chen, 1995). The enriched VC prepared from RP had a significantly higher content of available P in soils than the rest enriched VC This might be because of higher available P (olsen P) in the RP-augmented VC products. These results of increasing soil P availability with the use of RP-based farmyard manure have been reported by Biswas and Narayansamy (2006). The use of microbial inoculated VC containing PSB resulted in more dissolution of P from insoluble RP, increasing the available P content of soil compared to no microbial treatments.

The production of several organic acids or organic matter decomposition by the microorganisms is the principal mechanism for the solubilization of insoluble K (Kaviraaj and Sharma, 2003). Therefore, MC alone did not significantly change soil available K content due to its low mineralization. However, the application of MC-based VC increased the soil available K content due to the addition of K from MC and increased mineralization under the presence of microorganisms in the VC. Furthermore, WH contains higher K among the wastes, henceforth increasing the K availability on application into soil compared to PS-based VC. Similarly, microbial inoculated VC containing KSB increased solubilization of K from insoluble MC, thereby increasing the available K in soil compared to no microbial inoculation.

The Ca and Mg availability in soil was higher under DM-based VC application due to the higher content of Ca and Mg minerals than other rock minerals. The VC prepared from PS contained higher Ca and Mg than WH, increasing their availability on soil application.

The Fe and Mn availability in soil decreases due to a higher amount of carbonate in the soil. The presence of carbonate of Ca and Mg in the DM-related minerals may act as a strong absorbent for metals and could form complex salts like $FeCO_3$ and $MnCO_3$, thereby decreasing the availability of Fe and Mn in soil. In contrast, MC-enriched VC showed lower Fe and Mn availability due to the absence of $CO_3{}^{2-}$ in MC compared to DM. Between the wastes, PS-based VC resulted in higher Fe and Mn availability on the soil compared to WH-based VC. A higher level of OC in PS significantly increased soil microorganisms' biomass, possibly enhancing organic matter mineralization, thus increasing the potential of Fe and Mn mobility in soil (Lipoth and Schoenau, 2007; Marcato et al., 2009).

The Zn availability of soil is highly pH-dependent (Vítková et al., 2009). Therefore, with increasing the pH of the soil, the availability of Zn decreased in DM-enriched VC compared to MC and RP-enriched VC. This result was also reported earlier by Lindsay (1991), that hundred times decrease in Zn solubility can be observed by one unit increase in pH of soil. On the other hand, PS-based VC enhanced the Zn availability of soil due to the higher organic matter content that improved soil microbial population for better mineralization compared to WH-based VC.

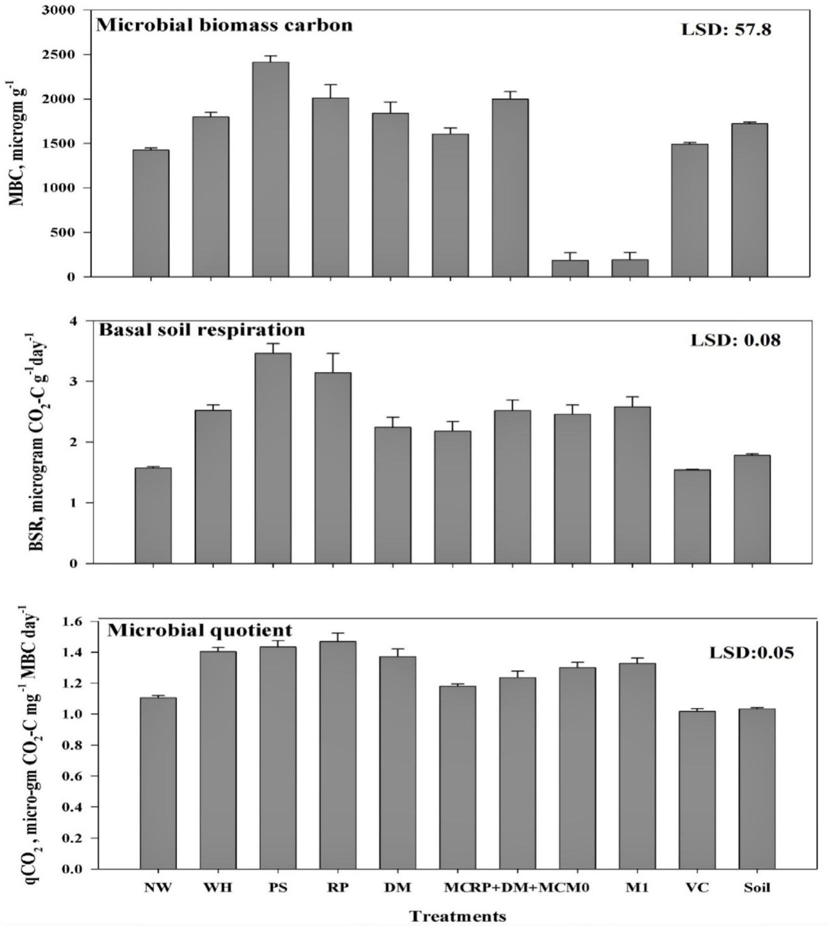

Fig. 7. Bio-chemical properties (microbial biomass carbon, basal soil respiration and microbial quotient) of soil as affected by different enriched vermicomposts; The vertical lines indicate standard error. LSD: least significance difference at P = 0.05; NW: no waste (only rock minerals); RP: rock phosphate; DM: dolomite; MC: mica; RP+DM+MC: mixed mineral; M0: without microbial inoculants; M1: with microbial inoculants; VC: conventional vermicompost.

4.2.2. Bio-chemical properties of soil

Microbial activities of soil

The MBC constitutes a small portion (1.5%) of the soil OC (Jenkinson and Ladd, 1981; Smith and Paul, 1990). but it is more dynamic and fluctuating than any other forms of soil OC over a short period. Thus, recording the MBC always proves better for judging the quality changes of VC (Ghosh et al., 2012). The higher MBC/soil OC means a higher amount of organic matter is mineralized (Yang et al., 2009); that is, more substrate available, and the portion of soil OC immobilized in the microbial cells (Yang et al., 2010). Higher MBC was observed in organically applied treatments compared to only rock mineral-treated soil reported by several researchers (Zhang et al. 2009; Dinesh et al., 2010; Preethi et al., 2013). The increased MBC in RP and mixed mineral treatments could be attributed to more OC to support the microbial community and steady nutrient release by decomposition. Improvement in MBC by adding organic amendments suggests that the soil of the experimental site is C-limited, and C- provided by the organic amendments was used as a source of energy by the microorganisms. The qCO_2 is the respiration per unit of microbial biomass and is a parameter of bio-energetic changes in a developing ecosystem (Odum, 1969); lesser qCO_2 means lesser consumption of C by microorganisms (Singh et al., 2022) for maintenance and progress towards maturity (Insam and Haselwandter, 1989; Anderson and Domsch, 1993). The highest value of qCO_2 was measured in RP-based VC (15.6 μg CO_2-C mg^{-1} MBC h^{-1}) (Fig. 7). This indicates the stress on the microbial population and in microorganisms to access more C for maintenance and growth.

Soil enzyme activities

The biochemical properties of soil have often been considered early and sensitive indicators for soil quality. The soil enzyme activities are closely associated with organic matter content (Beyer et al., 1993). The significantly higher APA in the RP-based treatment might be due to the enhanced PSB-containing phosphatase enzymes and their secretion intensity, which was limited by orthophosphate requirements (Martinez and Tabatabai, 2000). The application of RP-based enriched VC increased the available P content of the soil, increasing APA. The DM and MC-based VC reduced the APA due to the lower amount of available P sources in DM and MC. The APA was also closely related to the soil OC content ($r = 0.87^{**}$, $P < 0.01$) and MBC ($r = 0.65^{**}$, $P < 0.01$; Table 3). The variable urease activity observed in the soil obtained from direct enriched VC might be due to variations in the OC content of the initial content (Syers et al., 1979). High correlation value ($r = 0.76^{**}$) between the urease activity and basal soil respiration suggested the activity of the increasing micro-organisms in the soil that might be solely responsible for urease activity in the soil. Incorporating organic material into the soil usually increases the soil's MBC content (Mahajan et al., 2016). In our experiment, VC-related treatment showed higher MBC of soil (no application of VC), indicating a high amount of water-soluble carbon, carbohydrate, and mineralizable nitrogen, which acted as energy and nutrient sources for the microorganisms, thus contributing to increased microbial activity and biomass. RP-based VC improved soil microbial activity among the enriched VCs due to higher OC and available N content.

5. Conclusion

The present study demonstrates that using enriched and conventional VC sources significantly affects the soil OC content and the soil microbial and enzyme activities. Furthermore, the effect of traditional VC application was found to be more pronounced on soil OC stock and C-build-up than any other enriched VC. However, RP-enriched and MC-enriched VC resulted in higher soil P and K content, respectively. Therefore, the RP+DM+MC-based-VC improves macro and micronutrient content and more useful organic nutrient resources. Thus, enriched VC can be successfully applied to address the specific macro-nutrient deficiencies in acid-lateritic soils. Furthermore, compared to the other rock mineral treatments, RP+DM+VC and RP permeated VC showed considerably greater urease and acid phosphatase levels implying that such organics can perform equally well in the case of cereals and pulse crops. Additionally, the outcomes of the study indicate that the order of significance in enrichment was followed by the MBC content of the soil, demonstrating the capability of the proposed enrichment process in rejuvenating soil health. Therefore, we concluded that the conventional VC preparation process infused with technological advancements involving the rock minerals boosted the bench strength regarding nutrient content and soil rejuvenation potential of traditional VC.

CRediT authorship contribution statement

Debabrata Das: Conceptualization, Methodology, Visualization, Investigation, Formal analysis, Writing first draft, Software, Writing – review & editing. **Kumar Abbhishek:** Data curation, Writing, editing original draft. **Pabitra Banik:** Conceptualization, Supervision. **Dillip Kumar Swain:** Conceptualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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